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N-21925

CRUSTAL STRUCTURE IN THE WISCONSIN AREA

L. B. Slichter

Institute of Geophysics
University of California
Los Angeles 24, California

N9 onr-86200
October 31, 1951

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Summary:

Seismic results from six large blasts in the Wisconsin area are reported. The observations were made with a group of 12 three-component instruments, of period 1 second, located on selected bed-rock sites. Time signals at 1 second intervals were transmitted by radio. On the scale of the present experiments, which involved an area about 600 km. long by 150 km. wide, the major structure revealed was a relatively homogeneous layer about 40 km. thick. The time-distance segment corresponding to this layer is always nearly linear; and, at the four areas investigated implies compressional wave velocities of 6.16, 6.26, 6.22 and 6.16 km./sec. respectively. Although the assumption of a homogeneous layer of uniform wave velocity leads to satisfactorily small residuals (see Table I--the mean absolute value for 8 residuals for the Davenport blast is, for example, .09 seconds), an improved fit with the observed time-distance data results throughout the area if the wave velocity in the major layer is assumed to increase linearly with depth, in accordance with the relations:

$$v = 6.034(1 + .0038z) \quad \text{(Northern Area)}$$
$$v = 5.94(1 + .0045z) \quad \text{(Southern Area)}$$

where z = depth below top of layer in km.

In Table III is shown a summary of the seismic interpretations corresponding to several postulated crustal models. The preferred models, "Palmer III" and "Davenport II" incorporate, respectively, the two velocity functions above. A significant effect of the assumption of the increase in velocity with depth is the increase in thickness deduced for the major layer, and the decrease assignable to the thin overlying layer. The increase (see Table III) is about 15 %, but the decrease in the thickness of the superficial layer may vary from 25 % to several hundred percent. The residuals associated with the several crustal models specified in Table III are listed in Table I. Table I also lists complete Time-Distance data for compressional phases for the several blast locations. The non-homogeneous layer in model "Palmer III" avoids the ad-hoc split into two homogeneous layers involved in the two comparison equations T_2 and T_2'. The corresponding Davenport Model "Davenport II" removes a small systematic trend in the residuals for "Davenport I", and also reduces their mean absolute magnitude by about 1/2. Note, however, that the first arrival at Δ = 204.2 km. is definitely early on either basis. (See Figure 3, for reproduction of this seismogram.) This early arrival is attributed to the fast wave below the Mohorovičić discontinuity. Plans in 1940 to observe this phase at greater distances with subsequent Davenport blasts were necessarily abandonned due to the impact of the war. In deducing the depth to the Moho discontinuity at Davenport, it has been assumed that the wave-velocity, v_3, is 8.17 km./sec., as observed in the northern part of the area; and the early arrival at Δ = 204.2 is attributed to the v_3 phase. More extensive observational data throughout the area, is greatly to be desired in amplification of the present observations.

The scale of the present field work is obviously much too coarse for mapping the details of the thin superficial layer. The observed velocities in this layer vary from 4.16 to 4.58, and the thickness from .63 km. in the south to 2.8 km. in the north (basis of preferred interpretations). That the layer can not be subject to extremely large local fluctuations in thickness or wave velocity is evidenced by the generally small and regular residuals of the time-distance data with respect to smooth comparison functions. These residuals are generally less than .1 or .2 seconds, indicating that the local fluctuations in the layer thickness are generally less than .4 to 1.2 km. The travel-time data are indeed insensitive in the present case to variations in the thickness of the superficial layer.

Map 1 shows the distribution of the blast points and observing stations. Figures 1 to 4 reproduce 16 of the seismograms. In particular, Figure 1, Figure 2, Figure 3, ($\triangle$ = 143.3) and Figure 4 (e) and (f) show significant second arrivals. Figure 4 shows 6 pairs of "duplicate" records and the useful degree of similarity of such pairs. The Palmer records were duplicated pair-wise with an east-west separation of 2.8 km. between shot points in neighboring mines. Figures 4 (e) and 4 (f) exhibit comparisons of Palmer records at large epicentral distances. In Table II, the time-distance data are consolidated by reduction to a common origin time at $\triangle$ = 112.2 km. (i.e. the midpoint of the 6.16-6.26 km./sec. segments). This choice of origin relegates differences due to local conditions near the blast points to the initial, less significant part of the travel-time curve. The preferred interpretations lead to depths to the Moho of 40 to 44 km., with a thin superficial layer .6 to 2.8 km. thick, of wave velocity about 4.2 to 4.5 km./sec. In the major layer the velocity increases gradually from about 6.0 km./sec. at the top, to 7.0 km./sec. at the bottom. Below this layer, the compressional wave velocity is about 8.17 km./sec.

Map 1. Location of Blast and Observing Stations.

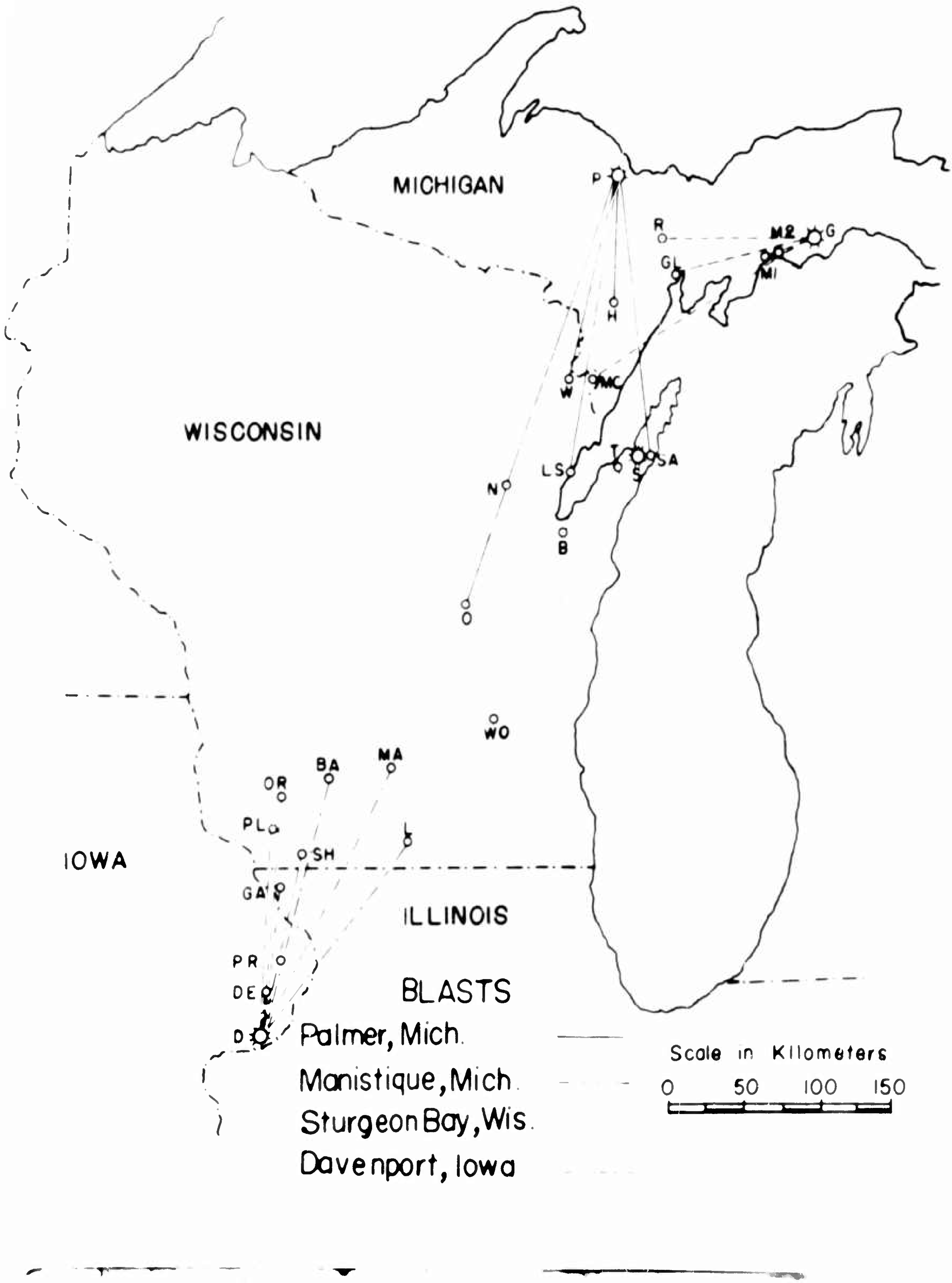
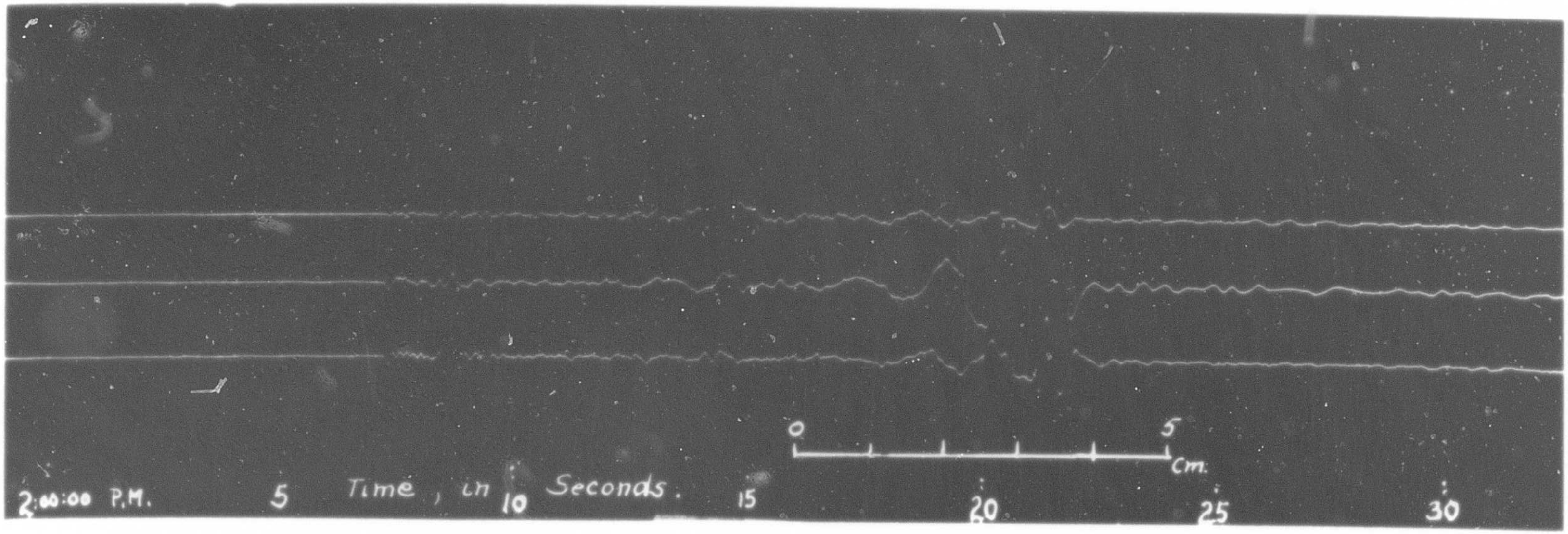

MICHIGAN
WISCONSIN
IOWA
ILLINOIS
P
R
M2
G
GL
MI
H
W
MC
LS
T
S
SA
N
B
WO
MA
BA
OR
PL
SH
L
GA
PR
DE
D
BLASTS
Palmer, Mich.
Manistique, Mich.
Sturgeon Bay, Wis.
Davenport, Iowa
Scale in Kilometers
0
50
100
150

Figure 1. Seismogram for Manistique, Δ = 34.13 km., Showing Second P Phase.



0
5
Cm.
2:00:00 P.M.
5
Time, in Seconds.
10
15
20
25
30

Figure 2. Seismogram for Palmer, $\triangle$ = 128.0 km., Showing second P Phase.

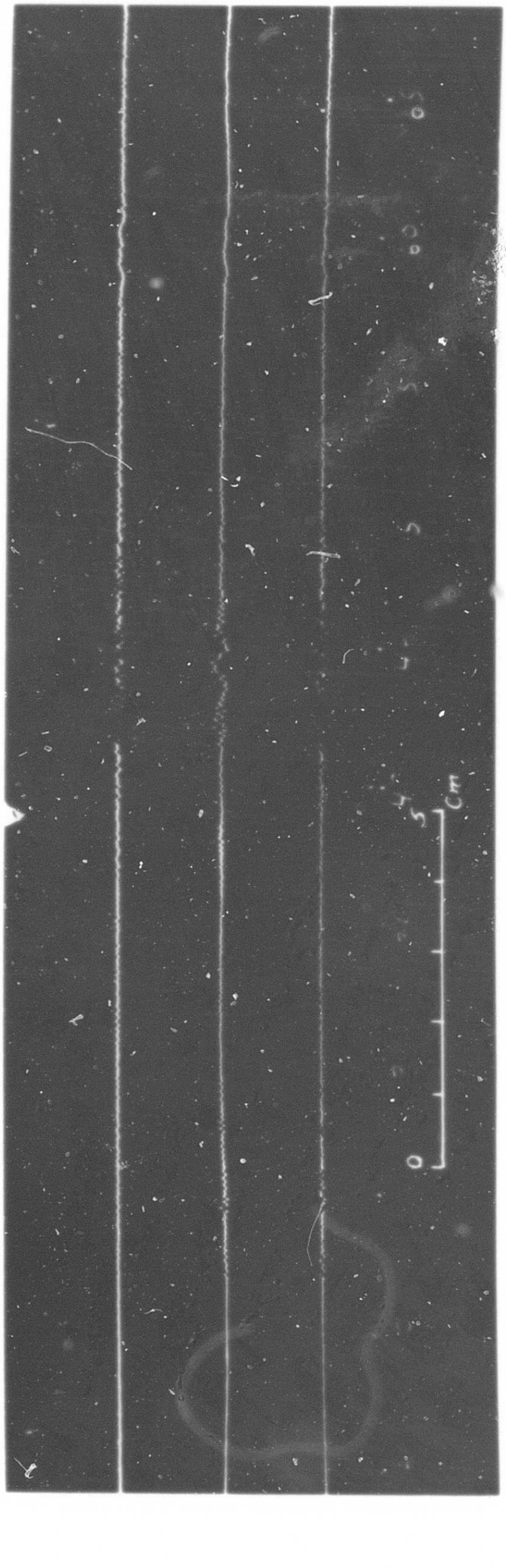
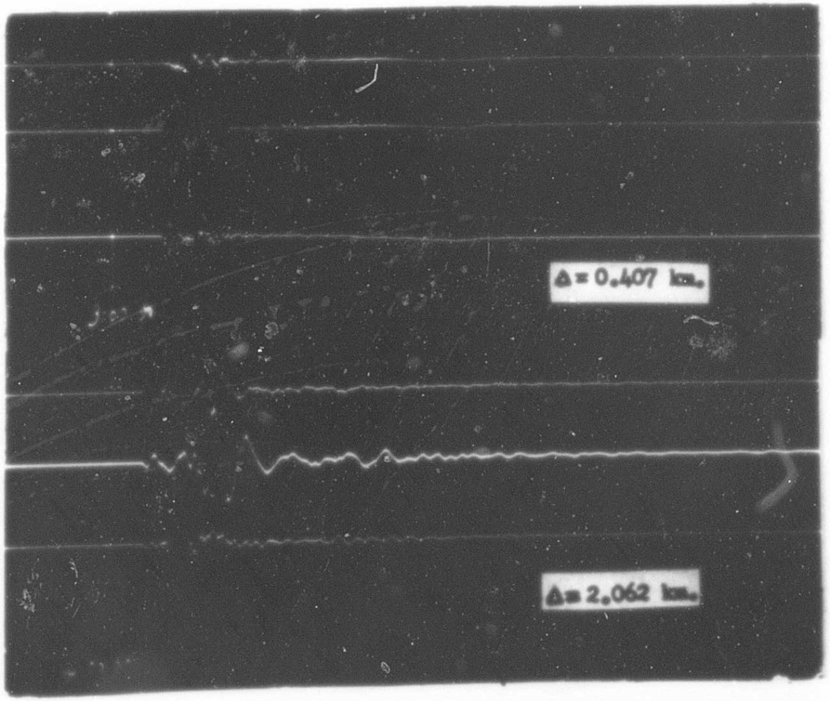
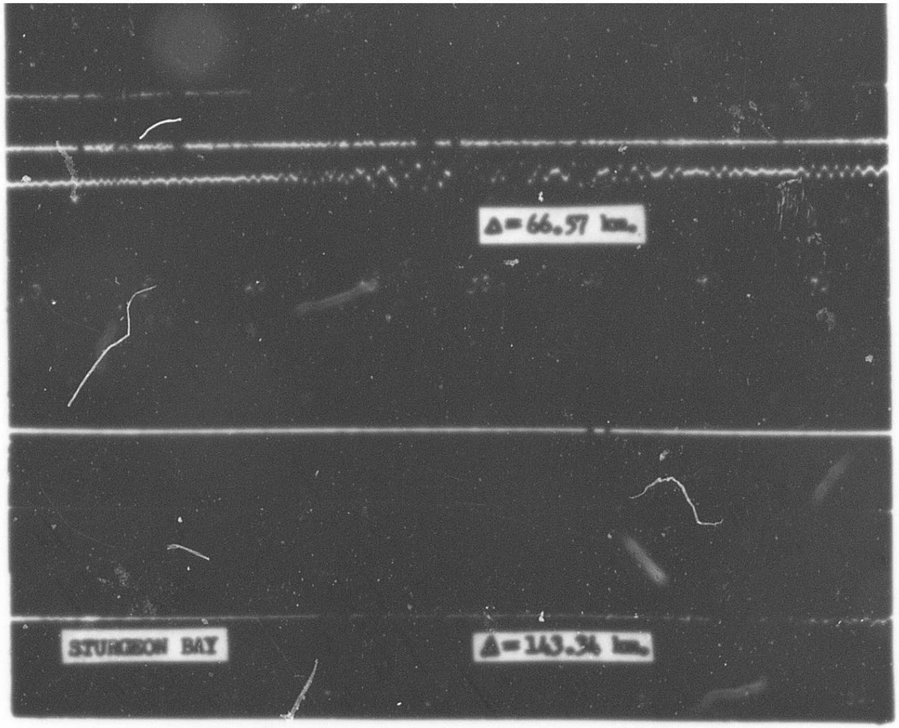

0
5
Cm

Figure 3. Seismograms for Sturgeon Bay, and Seismogram for Daven[illegible]

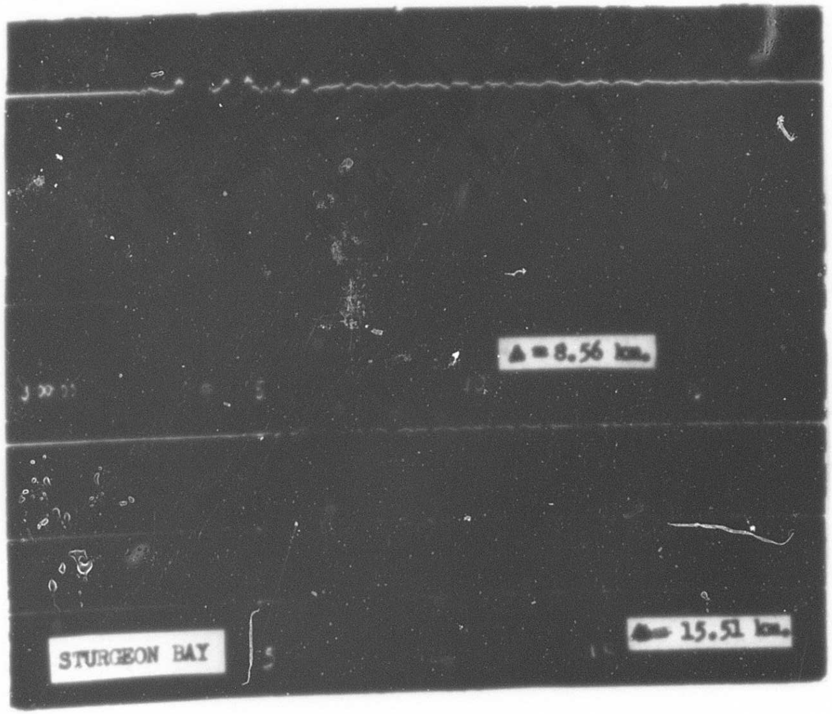
$\Delta = 204.2$



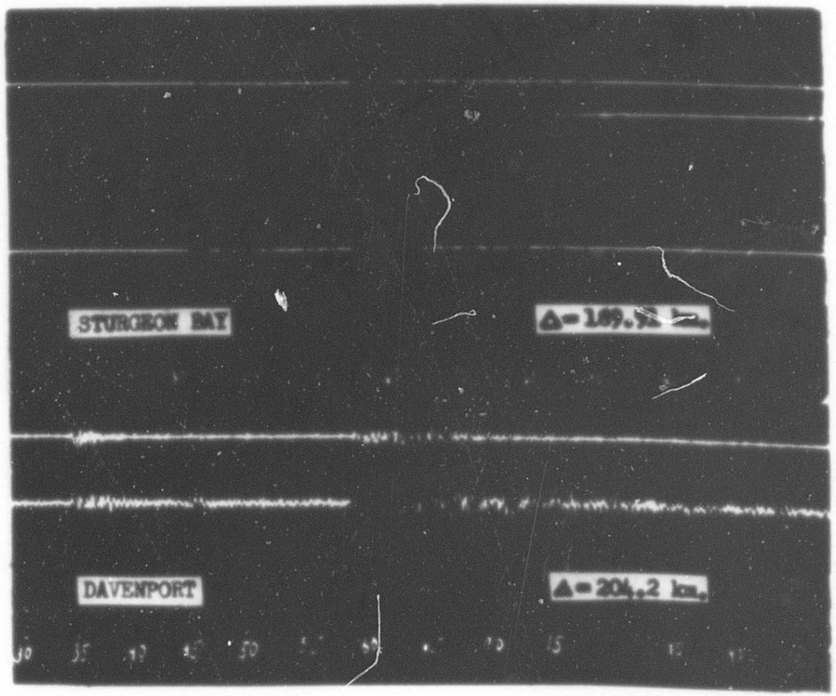
Δ = 0.407 km.
Δ = 2.062 km.



Δ = 66.57 km.
STURGEON BAY
Δ = 143.34 km.



Δ = 8.56 km.
STURGEON BAY
Δ = 15.51 km.



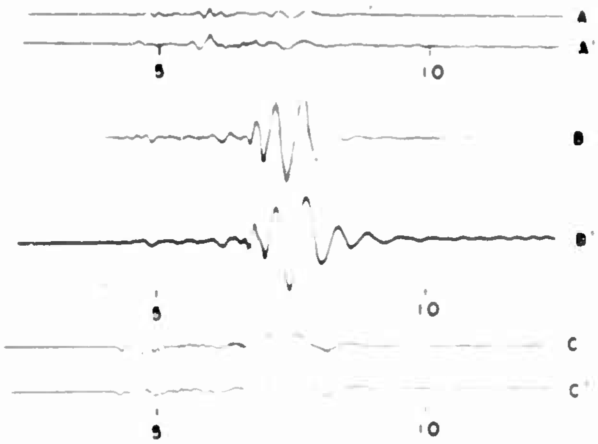
STURGEON BAY
DAVENPORT
Δ = 204.2 km.

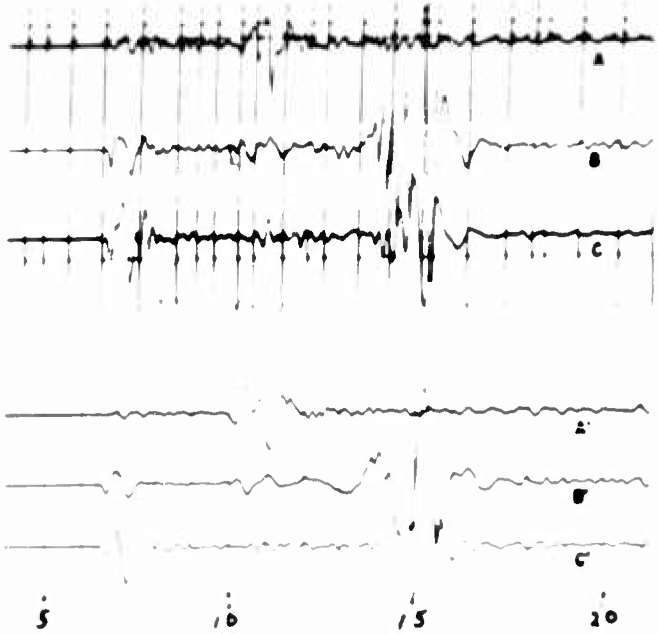
Figure 4. Record Pairs for Repeated Blasts. Epicentral Range 8.39 km. to 277.5 km.

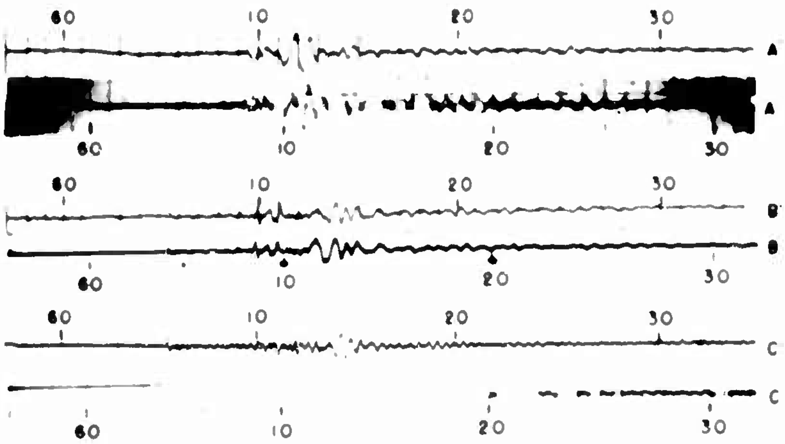
COMPARISON OF REPEAT SEISMOGRAMS

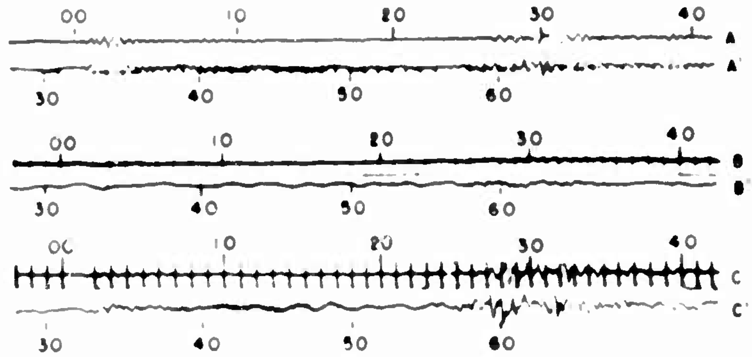
A, A' Transverse Component
B, B' Vertical Component
C, C' Longitudinal Component

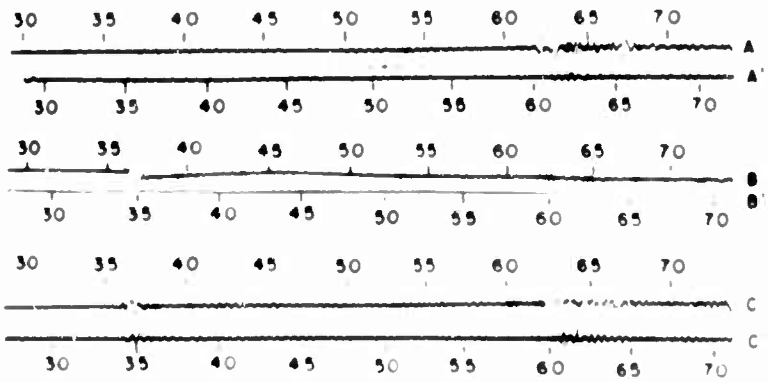
BLAST	DATE	POUNDS DYNAMITE	TRACE MARKS	EPICENTRAL	DISTANCE
				Fig. (a)	Fig. (b)
Manistique	June 22, 1940	47,000	A,B,C	8.51	21.16
"	Aug. 7, 1940	58,000	A',B',C'	8.39	21.46
				Fig. (c)	Fig. (d)
Hudson	June 15, 1939	30,000	A,B,C	32.20	204.5
"	Nov. 11, 1939	56,000	A',B',C'	32.70	204.5
				Fig. (e)	Fig. (f)
Palmer	July 20, 1940 a.m.	20,000	B,C	216.1	277.5
"	July 20, 1940 p.m.	13,000	B',C'	216.1	277.5











A B A' Omitted Record No Value

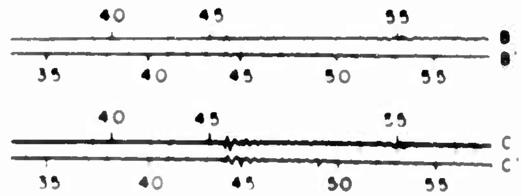


TABLE I

TRAVEL TIME DATA FOR COMPRESSIONAL PHASES

P A R T I. Palmer Mich. (20,000 lbs.) July 20, 1940 (t_o = origin time = 0 for Palmer Blast)

Station	Symbol	Δ, km	$t-t_o$ sec.	Comparison Equation I	T_1	Residuals $t-t_o-T_i$ I $\alpha = 0$	II $\alpha = .00307$	III $\alpha = .0038$	Remarks
Volunteer Mine, Mich.	V1	0	0	$T_1 = \Delta/4.16$	0.00	0.00			
" " "	V2	.57	.15	" "	.138	.002			
Palmer, Mich.	P	10.41	2.51	" "	2.51	0.00			
Hermansville, Mich.	H	84.83	14.95	$T_2 = \Delta/6.16 + 1.20$	14.97	−.02	−.002	−.032	
Wausaukee, Wis.	W	128.0	22.01	" " "	21.98	+.03	+.007	+.006	
Sawyer, Wis.	SA	179.4	30.30	" " "	30.32	−.02	−.007	+.009	
Sawyer, Wis.	SA	179.4	30.30	$T_2' = \Delta/6.58 + 3.03$	30.30	0.00	−.007	+.009	
Navarino, Wis.	N	216.1	35.80*	" " "	35.87	−.07	−.34	−.113	Strong; Note (1)
Omro, Wis.	O	277.5	44.2* ±.1	" " "	45.20	0.00	−.485	+.050	" " "
Wausaukee, Wis.	W	128.0	24.13*	$T_3 = \Delta/8.17 + 8.34$	24.01	+.12			Strong
Sawyer, Wis.	SA	179.4	30.30	" " "	30.30	−.01			High frequency
Little Suamico, Wis.	LS	188.5	31.35	" " "	31.41	−.07			
Navarino, Wis.	N	216.1	34.82	" " "	34.79	+.02			
Omro, Wis.	O	277.5	42.32	" " "	42.31	0.00			
Sawyer, Wis.	SA	179.4	31.30*	Reflection	31.14			+.16	
Little Suamico, Wis.	LS	188.5	32.67*	"	32.42			+.25	High frequency
Wausaukee, Wis.	W	128.0	24.13**	"	24.12			+.01	Alternative Interpretation

Note (1) On basis of $T_2 = /6.16+1.20$ these residuals would be −.48 and −1.05 respectively.

P A R T II. Manistique, Mich. #1 (47,000 lbs) June 22, 1940; #2 (58,400 lbs) Aug. 8, 1940.
(t_o = .70 for Manistique #1; t_o = 1.95 for Manistique #2)

Station	Symbol	Δ, km	$t-t_o$ sec.	Comparison Equation I	T_1	I	II	III	Blast No.
Gulliver (1) Mich.	G1	.00	.00	$T_1 = \Delta/4.53$	0	0			#1, #2
Gulliver (2) Mich.	G2	.33	.07	" "	.073	−.003			#1
Gulliver (3) Mich.	G3	.68	.15	" "	.15	0			#2
Gulliver (4) Mich	G4	8.39	2.20	" "	1.85	+.35			#2
Manistique (2) Mich.	M2	21.46	4.61	" "	4.74	−.13			#2

Table I   Travel-Time Data for Compressional Phases, and Residuals Corresponding to Several Crustal Models.

PART IV Davenport, Iowa. (34'000 lbs) May 29, 1940

Station	Symbol	Δ, km	$t-t_o$ sec	Comparison Equation T_i	T_i	Residual $t-t_o-T_i$ I $\lambda = 0$	Residual $t-t_o-T_i$ II $\lambda = .00449$	Remarks
			$t_o = .90$					
Quarry, Dewey Portland	D1	.00	.00	$T = \Delta/4.5$	.00	.00		
Cement Co.	D2	.45	.10	" "	.10	.00		
DeWitt, Iowa	DE	35.60	6.25	$T_2 = \Delta/6.16 + .55$	6.33	-.08	+.086	
Preston, Iowa	PR	72.19	12.24	" " "	12.27	-.03	-.039	
Galena, Ill.	GA	108.0	18.24	" " "	18.08	+.16	+.064	
Sholisburg, Wis	SH	128.0	21.45	" " "	21.33	+.12	+.017	
Platteville, Wis.	PL	144.6	24.10	" " "	24.03	+.07	-.010	
Linden, Wis.	L	165.0	27.25	" " "	27.34	-.09	-.099	
Orfordsville, Wis.	OR	177.2	29.23	" " "	29.32	-.09	-.038	
Barneveld, Wis.	BA	185.6	30.60	" " "	30.68	-.08	+.023	
Madison, Wis.	MA	204.2	33.20	" " "	33.70	-.50	-.246	See text
Madison, Wis.	MA	204.2	33.20	$T_3 = \Delta/8.17 + 8.206$	33.20	0		

* Second Arrival
** Third Arrival

Station	Symbol	Δ, km	$t - t_o$ sec	Comparison Equation T_i	T_i	Residuals $t - T_i$ I ($\alpha = 0$)	II	III ($\alpha = .0038$)	Remarks
									Blast No.
Manistique (1) Mich.	M1	34.13	7.54*	$T_1 = \Delta/4.53$	7.54	.00			Blast #1
Gulliver (4) Mich.	G4	8.39	2.47*	$T_2 = \Delta/6.26+1.00$	2.34	+.13			" #2
Manistique (2) Mich.	M2	21.46	4.61	" " "	4.43	+.18			" #2
Manistique (1) Mich.	M1	34.13	6.46	" " "	6.46	.00		-.17	" #1
Rock, Mich.	R	101.1	16.95	" " "	17.15	-.20			" #2
Gladstone, Mich.	GL	102.0	17.06	" " "	17.29	-.23			" #2
McAllister, Wis.	MC	168.1	27.85	" " "	27.85	.00		-.56	" #1
McAllister, Wis.	MC	168.1	29.25*	Reflection				-.30	1 Clear Event
PART III. Sturgeon Bay, Wis. (10,650 lbs) July 2, 1940 (t_o=0)									
Quarry, Sturgeon Bay Co.	S1	.00	.00	$T_1 = \Delta/4.58$	.00	.00			
" " " "	S2	.41	.37	" "	.09	.28			See text
Sturgeon Bay, Wis.	S3	2.06	.45	" "	.45	.00			
Sawyer, Wis.	SA	8.56	1.87	" "	1.87	.00			
Sawyer, Wis.	SA	8.56	1.87	$T_1' = \Delta/5.74+.38$	1.87	.00			
Tornado, Wis.	T	15.51	3.02	" " "	3.08	-.06			Note (1)
Bellevue, Wis.	B	66.57	11.97	" " "	11.97	.00		-.014	
Bellevue, Wis.	B	66.57	11.97	$T_2 = \Delta/6.22+1.27$	11.97	.00			
Omro, Wis.	O	143.3	24.31	" " "	24.31	.00		-.159	
Omro, Wis.	O	143.3	25.41*	$T_3 = \Delta/8.17+8.30$	25.84	-.43			Clear Event
Woodland, Wis.	WO	189.9	31.55	" " "	31.55	.00			Note (2)
Bellevue, Wis.	B	66.57	16.3*	Reflection					Shear Comp.
Woodland, Wis.	WO	189.9	33.0	"					" "

Note (1) On Basis of Comparison Line T_1, this Residual would be -.37
Note (2) " " " " " T_2, " " " " -.25

Table II Consolidated Travel-Time Data Reduced to Common Origin at $\Delta = 112.2$ km.

TABLE II

Composite Travel-Time Data, Adjusted to Common Point. Δ = 112.2, t = 19.41

Symbol	Blast	Δ km.	t_A, sec	Comparison equation	Ti	Residual t_A-Ti	Remarks
V1	P	.00	.00	$T_1 = \Delta/4.2$	.00	.00	
G1	M1,M2	.00	.56		.00	.51	
S1	S	.00	.11		.00	.11	
D1	D	.00	.65		.00	.65	
G2	M 1	.33	.63		.078	.55	
S2	S	.41	.48		.097	.38	
D2	D	.45	.75		.107	.64	
V2	P	.57	.15		.136	.01	
G3	M 2	.68	.71		.162	.55	
S3	S	2.06	.56		.49	.05	
SA	S	8.56	1.98		2.04	-.06	
P	P	10.41	2.51		2.48	.03	
M2	M 2	21.46	5.17		5.11	.06	
M1	M 1	34.13	8.10*		8.10	.00	
SA	S	8.56	1.98	$T_1 = \Delta/5.74 + .49$	1.98	.00	
T	S	15.51	3.13		3.19	-.06	
B	S	66.57	12.08		12.08	.00	
G4	M2	8.39	2.76	$T_2 = \Delta/6.18 + 1.26$	2.62	.14	
M1	M1	34.13	7.02		6.78	.24	
DE	D	35.6	6.90		7.02	-.12	
B	S	66.6	12.08		12.04	.04	
PR	D	72.2	12.89		12.94	-.05	
H	P	84.8	14.95		14.98	-.03	
R	M2	101.1	17.51		17.62	-.11	
GL	M2	102.0	17.62		17.77	-.15	
GA	D	108.0	18.89		18.74	.15	
SA	D	128.0	22.10		21.97	.13	
W	P	128.0	22.01		21.97	.04	
O	S	143.3	24.42		24.45	-.03	
PL	D	144.6	24.75		24.66	.09	
L	D	165.0	27.90		27.96	-.06	
MC	M 1	168.1	28.41		28.46	-.05	
OR	D	177.2	29.88		29.93	-.05	
SA	P	179.4	30.30		30.29	.01	
BA	D	185.6	31.25		31.29	-.04	
LS	P	188.5	31.35		31.76	-.41	
MA	D	204.2	33.85		34.30	-.45	
SA	P	179.4	30.30	$T_2 = \Delta/6.58 + 3.03$	30.30	0	
N	P	216.1	35.80*		35.87	-.07	
O	P	277.5	45.20*		45.20	.00	

TABLE II (Continued)

W	P	128.0	24.13*	$T_3 = \Delta/8.17 + 8.34$	24.01	.12	
O	S	143.3	25.52*		25.87	-.35	
MC	M1	168.1	29.81*		28.92	.89	
SA	P	179.4	30.30		30.30	.00	
L3.	P	188.5	31.35		31.41	-.06	
WO	S	189.9	31.66		31.57	.09	
N	P	216.1	34.82		34.79	.03	
O	P	277.5	42.32		42.32	.00	
MA	D	204.2	33.85	$T_3 = \Delta/8.17 + 8.86$	33.85	.00	see text
MC	M1	168.1	29.81	Reflection	29.76	.05	see text

* Second Event

Note: The following time adjustments were added to the listed values of $t - t_o$ in Table I to bring the travel times into accord at $\Delta = 112.2$: Palmer blast, 0; Manistique blasts, .56 sec.; Sturgeon Bay, .11 sec; Davenport, .65 sec.

Table III Summary of Interpretations.

TABLE II[illegible]

Summary of Inter[illegible]tions

PALMER			MANISTIQUE	STURGEON BAY		DAVENPORT	
Model I	Model II	Model III	Model I	Model I	Model II	Model I	Model II
$\alpha = 0$	$\alpha = .00307$	$\alpha = .0038$	$\alpha = 0$	$\alpha = 0$	$\alpha = 0$	$\alpha = 0$	$\alpha = .00449$
$v_1 = 4.16$	$v_1 = 4.16$	$v_1 = 4.16$	$v_1 = 4.53$	$v_1 = 4.58$	$v_1 = 4.58$	$v_1 = 4.5$	$v_1 = 4.5$
$v_2 = 6.16$	$v_2 = 6.034(1+.00307z)$	$v_2 = 6.034(1+.0038z)$	$v_2 = 6.26$	$v_2 = 6.22$	$v_2' = 5.74$ $v_2 = 6.22$	$v_2 = 6.16$	$v_2 = 5.94(1+.00449z)$
$v_3 = 8.17$	$v_3 = 8.17$	$v_3 = 8.17$	Not Determined	$v_3 = 8.17$	$v_3 = 8.17$	$v_3 = (8.17)$	$v_3 = (8.17)$
$t_1 = \Delta/4.16$	$t_1 = \Delta/4.16$	$t_1 = \Delta/4.16$	$t_1 = \Delta/4.53$	$t_1 = \Delta/4.58$	$t_1 = \Delta/4.58$	$t_1 = \Delta/4.5$	$t_1 = \Delta/4.5$
$t_2 = \Delta/6.16 + 1.2$			$t_2 = \Delta/6.26 + 1$	$t_2 = \Delta/6.22 + 1.27$	$t_2 = \Delta/5.74 + .38$	$t_2 = \Delta/6.16 + .55$	
$t_3 = \Delta/8.17 + 8.34$	$t_3 = \Delta/8.17 + 8.34$	$t_3 = \Delta/8.17 + 8.34$			$t_2 = \Delta/6.22 + 1.27$	$t_3 = \Delta/8.17 + 8.21$	$t_3 = \Delta/8.17 + 8.21$
				$t_3 = /8.17 + 8.30$	$t_3 = \Delta/8.17 + 8.30$		
	$v(h_2) =$ 6.717 km./sec	$v(h_2) =$ 6.904 km./sec					$v(h_2) =$ 7.09 km./sec.
$h_1 = 3.4$ km.	2.7 km.	2.80	$h_1 = 2.94$	$h_1 = 4.3$	$h_1 = 1.44$ $h_1' = 6.05$	$h_1 = 1.8$	$h_1 = .63$
$h_2 = 32.7$	36.9 km.	37.95		$h_2 = 32.1$	$h_2 = 30.0$	$h_2 = 35.3$	$h_2 = 42.95$
Depth to Moho=36.1	39.6 km.	40.75		36.4	37.49	37.1	43.58